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Performance of a prototype detector for use as the sweeping magnet photon-veto in the KOPIO experiment

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ABSTRACT: A detector system for use as a gamma (γ) veto in the volume of the high field of the sweeping magnet of the KOPIO experiment at BNL is presented here. A laminar design of alternating 5 mm plastic scintillator tiles and 2.54 mm Pb sheets was used. The scintillator signals were readout on both ends by embedded Kuraray Y11-200 multi-clad wave-shifting 1 mm $\times$ 19 fibers/tile (WSF). The calibration of the detectors through the single photo-electron (spe) peak of the photomultiplier tubes (PMTs) and the light attenuation measurements of the fibers were performed using a commercial light emitting diode (LED, blue 465 nm) pulsed with 30 ns pulses at 1kHz. Absolute light yield of a single tile averaged 60 pe per minimum ionizing particle (mip) from cosmic rays. An assembly of 10 scintillator layers combined with nine Pb layers yielded ~400 pe/mip. Light intensity attenuation of about 1 dB/m allows the embedded fibers to be extended to lengths of more than 6 m in order to carry the detector signal to PMTs outside the magnetic field, thus simplifying the readout.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Large detector systems for particle and astroparticle physics; Gamma detectors (scintillators, CZT, HPG, HgI etc).

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2006 JINST 1 P06004

Contents

2006 JINST 1 P06004

1. Introduction

The KOPIO experiment was one experiment of the Rare Symmetry Violating Processes (RSVP) project. Although the project was canceled by the USA National Science Foundation in 2006 due to cost, the experimental design was previously accepted and was to be run at the Alternating Gradient Synchrotron (AGS) accelerator of the Brookhaven National Laboratory [1]. Its goal was to produce a neutral K_L beam of sufficient intensity to measure the branching ratio (BR) of the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$, in search of valuable insight about CP violation and flavor mixing in the Standard Model (SM). It is a 3-body decay, however, the only observables are the 2gammas from the π^0 decay. The experiment aimed for a 10% measurement of the CP violating phase of the SM. A proton beam, resonantly extracted into micro-bunches with RMS widths of about 200 ps every 40 ns, would create K_L at a platinum target. The times and directions of photons from the π^0 decay would be observed in the preradiator-calorimeter combination of the detector (figure 1). They could be used to reconstruct the decay vertex position and determine the precise formation time and momentum of the K_L. Every other decay is considered a background and must be vetoed. The decay of interest has an expected BR of 3×10^{-11} of all the K_L decays out of which 34% of the time there is at least one π^0 that can fake the two gamma-rays signature. A very efficient and hermetic veto system is essential in the face of this enormous background. The coverage of the charged particle and γ-veto system had to be extended everywhere even through the high field of a sweeping magnet.

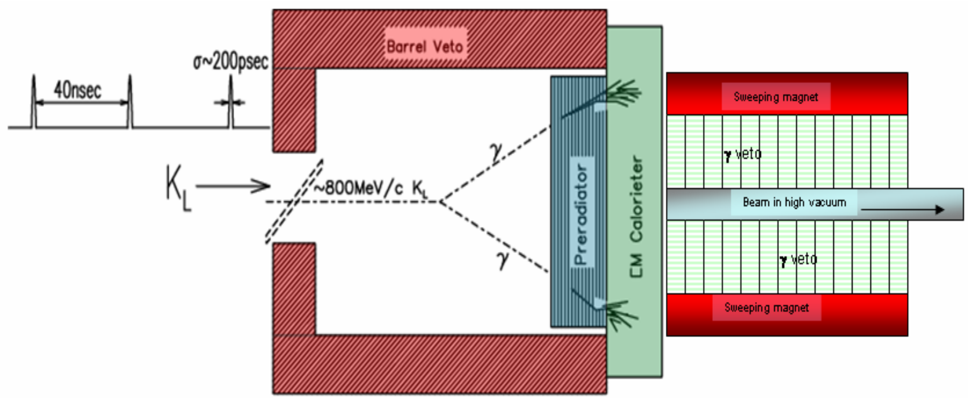

Figure 1. An illustration (not in scale) of the main KOPIO detectors. From left to right: Barrel veto, Preradiator, Calorimeter, Sweeping Magnet γ-veto. The veto system extends up and downstream from these. The vetos atop the beam pipe are not shown for clarity.

The γ-vetos in the area of the magnet were designed as alternating layers of scintillator tile and Pb sheets. The tiles would be read out from each end with WSFs. Modules would be 2 m long and contain 21 tiles sandwiching 20 layers of lead. Eighty such modules arranged on all four sides around the beam pipe would be placed in rough vacuum. They would cover a length of 3.5 m of the magnet's field along the beam direction.

Although the KOPIO experiment will not use this technology, many other current experiments adopt the layered tile scintillator-Pb with WSF readout to cover economically large areas in a set-up. Therefore, we present here a description of the performance of two small prototypes for the γ-ray veto-detectors that can operate in the harsh environments of high magnetic fields and vacuum and can easily be adapted for the needs of any similar experiment.

2. Prototype design

The scintillator tiles used in the prototypes are of dimension 50 cm $\times$ 15 cm and 5 mm thick are extruded polystyrene with white reflective paint etched on their surface [2]. The light yield is about 80% of that from Bicron BC408 scintillator. The necessary density of grooves per tile as well as their cut profile has been investigated previously [3]. Here there are 19 grooves per tile, spaced about 7 mm apart, with a simple U-channel profile for seating 1 mm diameter OD fibers running parallel to the long direction. Kuraray Y11-200 multi-clad WSF absorb in the blue region of the visual spectrum and re-emit in the green above 500 nm. Fibers of length 1.3 m were seated glued in the grooves with optical epoxy (Bicron BC60). At both tile ends the fibers were gathered together, finely sanded flat to an optical finish and coupled with optical grease to PMTs).

One such tile constituted the "single-tile" prototype while an assembly of 10 such scintillators combined with nine Pb layers is the "half-size" prototype in this work.

The PMTs used were the 1 inch (25.4 mm) Burle 83112-511 with the built-in base (the new version of the S83062E). The quantum efficiency (QE) is ~25% for λ = 450 nm with a photocathode responsivity (PR) of ~94 mA/W and QE ~10% at 550 nm with a PR ~45 mA/W. The nominal gain is 2.4×10^{6} at 1000 V, and 27×10^{6} at 1500 V as the photocathode is specifically coated for high gain. A batch of tubes with ratio ~1.2 of the width of the single photo-electron (spe) peak over its position with respect to zero [4] (equivalent noise) were used as they allowed a clear calibration of the PMTs (figure 2).

2006 JINST 1 P06004

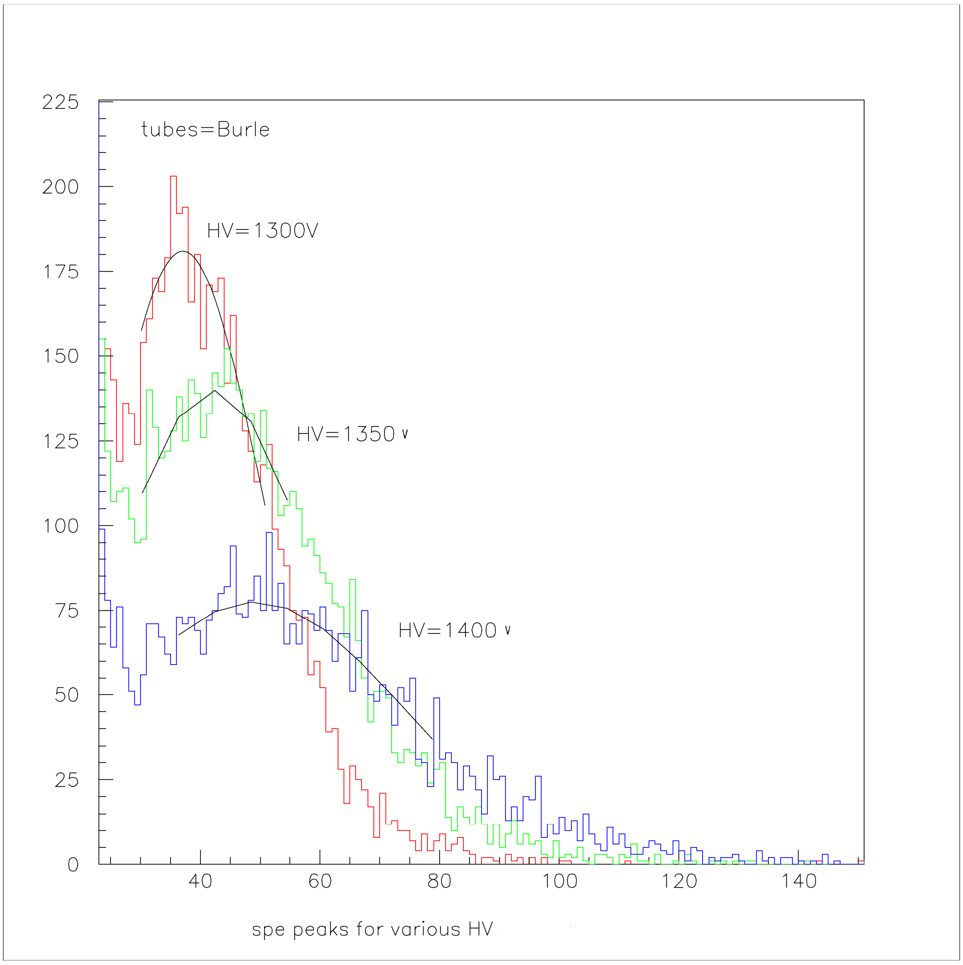

Figure 2. Single photo-electron spectra from a blue LED on a Burle PMT, parameterized for its HV and fixed LED pulser amplitude 870 mV.

3. PMT calibration

The PMTs were calibrated in units of pe using their (spe) peak. The source used was a commercial blue LED (from RadioShack® #276-311) with emission wavelength 465 nm and normal operation at 3.5 Vdc forward voltage.

The LED was driven by a HP8082A pulse generator with positive square pulses forward biasing the diode for 30 ns at 1 kHz. With pulse amplitude 870 mV, less than 0.1 pe/pulse of light is emitted from the diode as figure 2 illustrates. That means that, even at direct exposure of the LED onto the PMT, the probability is > 90% per pulse that the light emitted from the diode has not enough energy to cause even one pe to be emitted from the photocathode. The digitizing system registers zero energy (pedestals) within the 150 ns of the integration gates for 90% of the triggers. The gates are triggered by a properly delayed signal-out of the pulser. The high frequency of the sampling for the spe makes negligible any contribution of dark current or electronic noise above 30 mV (< 0.035% of triggers) to the spe peak. At even lower pulse amplitudes, the spe peak would not change position. It changes though with the PMT high voltage (HV).

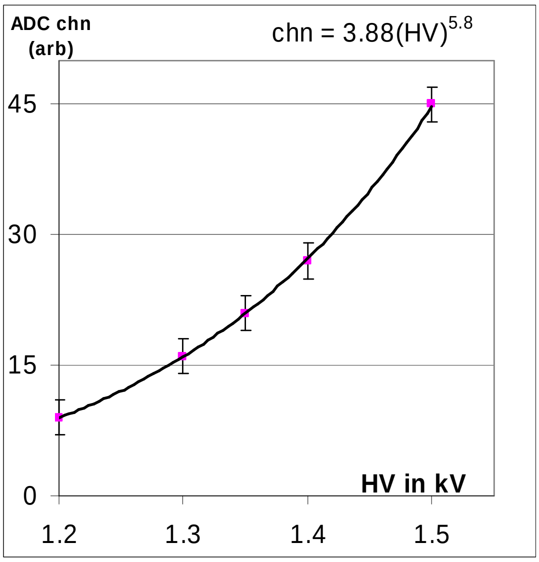

Figure 3. Gain curve of one of the Burle PMTs by the position of the spe with respect to the PMT HV. It varies as $a(HV)^b$ [4].

The spe peak position with respect to the zero value as a function of the PMT-HV was found for each tube, effectively mapping out a measure of the gain as a function of HV. Figure 3 shows that the gain can be fit, as expected [4], with a power curve, Gain=$a(HV)^{n*0.6}$ where n is the 10 stages of the PMT amplification system. The HV for these tubes, during the absolute light yields measurements, was chosen in the middle of the gain curve. Although the stability of the light output of a LED is no better than 5% that does not enter in the spe peak determination.

4. Light yield of a single tile

The absolute light yield measurements of both prototypes were performed with cosmic radiation. Muons with energy around 2 GeV are the typical cosmic ray constituent and they deposit about 1 MeV in the 5 mm tile.

A single tile of detector was placed in a cosmic ray telescope made of 3 small trigger scintillators of 2`` × 2`` each. One above the tile and two below signaled the passage of minimum ionizing particles (mip) traversing perpendicularly through the tile (less than 5% excess path through a tile at maximum inclination from the vertical). The cosmic ray signature was a triple coincidence of the trigger counters that formed an analog-to-digital (ADC) 30 ns gate for energy integration.

Figure 4 shows the results of the absolute light yield measurements. To ensure uniformity of fabrication and exclude differences in performance of the PMTs as a reason for error in the determination of the performance level of this prototype both orientations of the tile were tested under the same conditions. The particular choice for orientation as 1 or 2 was arbitrary. Nevertheless, orientation-1 yielded 58 pe/mip and orientation-2 yielded 62 pe/mip. They are in a very good agreement and demonstrate the excellent symmetry of the output. These results also indicate that for a 1 MeV energy deposit in a single tile, the light yield at each end is ~30 pe/MeV/side or 6 pe/mm/side. The error in the determination of the number of pe was estimated at 5%.

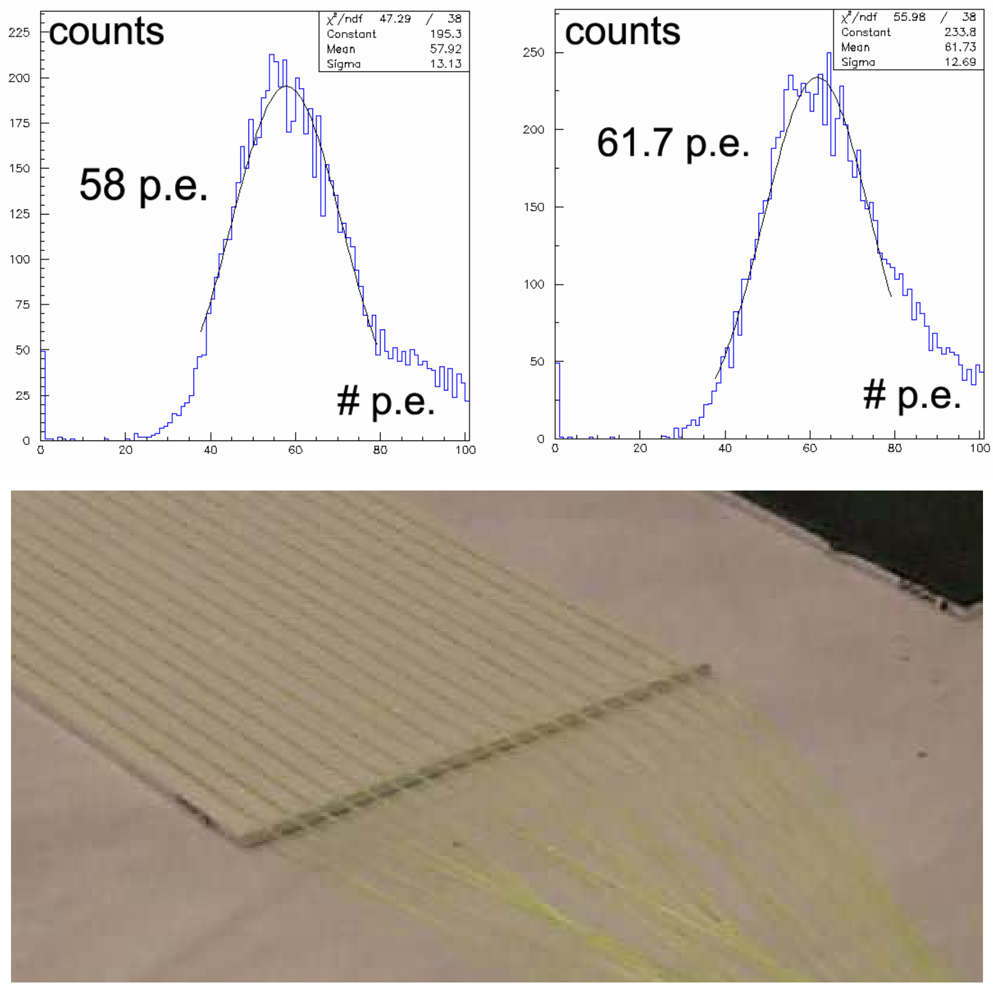

Figure 4. Light output from cosmic rays traversing the tile. The average output from both orientations is about 60(5) pe/mip (orientation-1 is top-left). A detail of the single layer prototype is in the bottom picture.

5. Time response of single tile

The trigger from the cosmic-ray coincidence was also used as a Start-gate in a time-to-digital converter (TDC). The signals from the two PMTs at the two ends of the detector shaped by leading-edge discriminators (30 mV threshold) made up the TDC individual (T1 and T2) Stop-gates. The absolute times T1 & T2 measure the time the light travels in the scintillator tile and the fibers as well as the individual delays in the lines of the electronic logic and it is of no interest. The spread of the average (T1+T2)/2 of the time-signals for each event provides a characterization of the timing accuracy and resolution of the detector. Figure 5 shows the results for the time resolution measurements (for the two orientations of the previous paragraph) histogrammed in 200 ps bins. The peak (in either orientation) has the offset proportional to the length of the path of the light in the detector and fibers, but there are no events outside the main peak. There is an excellent agreement with other work [3] for the time resolution of both orientations, close to 1.2 ns. Presumably, this can be improved using transient digitizers with thresholds lower than 30 mV. For γ-vetos, there would usually be much more than 1 MeV deposited and the timing would be better.

2006 JINST 1 P06004

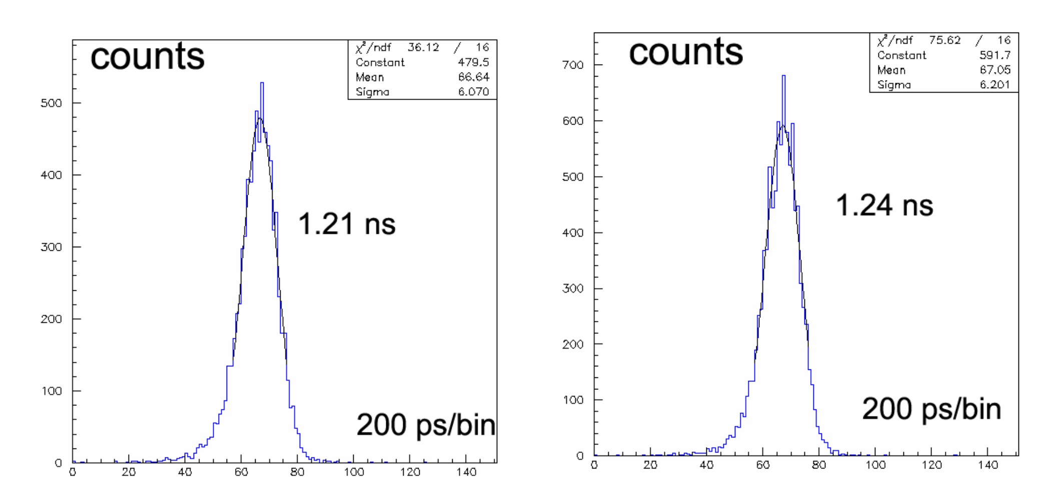

Figure 5. Time resolution from the average (T1+T2)/2 per event triggered with cosmic rays traversing a single scintillator tile. Offset is arbitrary. Orientation-1 is left.

6. Half-size prototype

The same measurements were performed on a half size prototype γ-veto detector. Ten scintillators tiles, cut at lengths of 50 cm each, were prepared as described above with embedded fibers of 1.3 m, and were glued together with nine Pb sheets in between (figure 6 right). During performance tests with cosmic ray triggers it yielded 400 pe/mip total with the

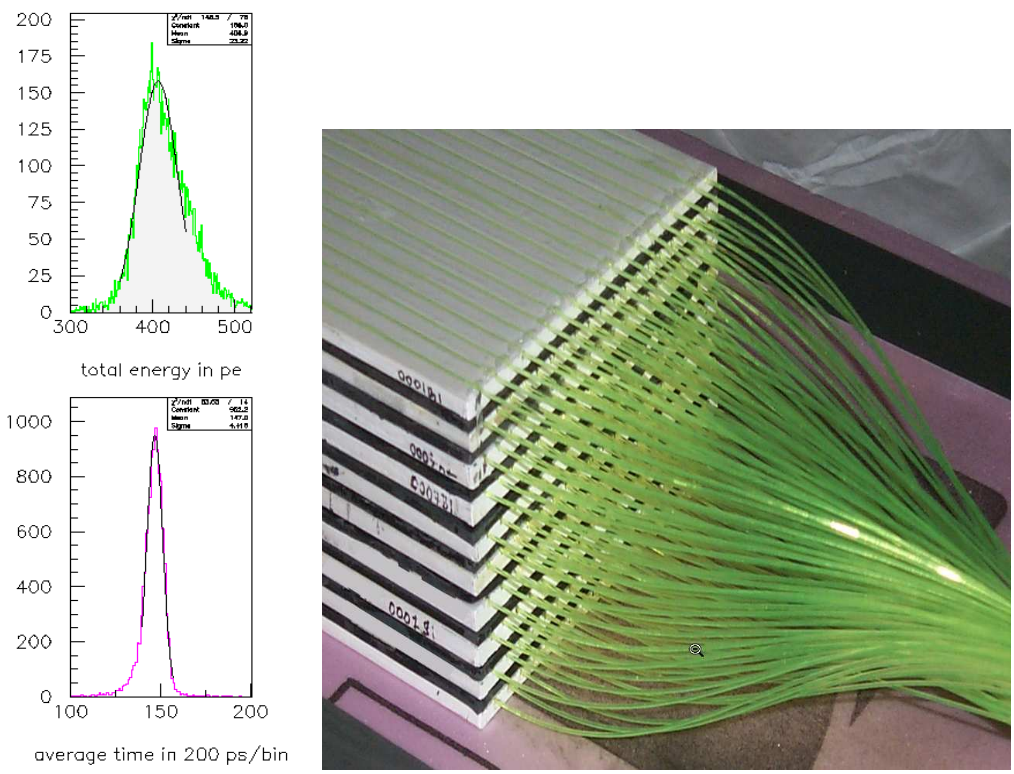

Figure 6. (Top-left) Light yield of the 10-layer prototype from cosmic rays ~400 pe/mip. (Bot-left) Time spread of the response is 0.88 ns improved as predicted from the time response of the single tile prototype. (Right) A detail of the detector prototype.

2006 JINST 1 P06004

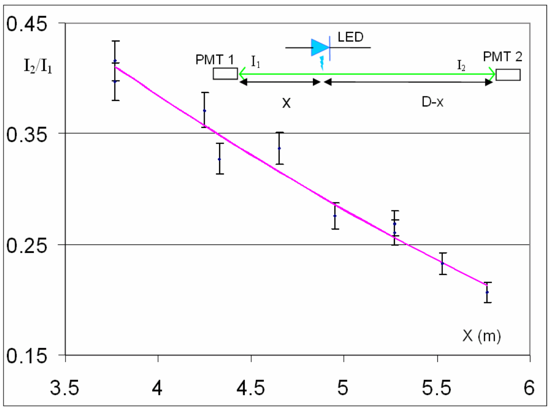

Figure 7. Light attenuation measurements of the KMC fibers. Twelve WLS fibers exposed to a blue (465 nm) LED, D = 6.25 m the total length of the fibers in the test. I_1 & I_2 are light intensities through the fibers (in pe), "x" is the distance (m) of the light source from PMT 1 (arb choice). Plotted here is the ratio of the light intensity vs. x (arb. choice). The points are fitted to a ratio of a sum of two exponentials.

PMTs running at a slightly lower gain (figure 6 top-left). The time resolution of the detector was 0.88 ns (figure 6 bot-left). The expected improvement was due to the response of the leading edge discriminators to higher amplitude signals from the PMTs that give better resolution.

7. Light attenuation in the fibers

The light attenuation coefficients of the KMC-WLS fibers were measured with the same LED source shining on a group of 12 such fibers. The source was positioned at various points along their 6.25 m length (figure 7). The light that was trapped and transported along the fibers was detected at both ends by PMTs.

The attenuation, as a function of the distance between the light source and the fiber end, can be expressed as a sum of two exponentials with a coupling constant (cc) multiplied to one of them [5]. They represent the self-absorption (short), exhibited by all compounds that have wavelength-shifting fluors and bulk (long) attenuation processes (geometrical optics factors). It is a common experience in the field [6] that the randomness of light absorption in the fibers accounts for fluctuations in intensity at the fiber ends that are comparable to the attenuation that was being measured here.

A normalization of the light intensities I_1, I_2 from the two ends comes from the fact that for each event and at each measurement point they correspond to the same burst of light from the pulsed LED or simply the same amount of light that was trapped in the fibers at the neighborhood of the position of the measurement (i.e. they are self-normalized). The ratio I_2/I_1 for each event is then normalized to all other events from the same calibration and the fluctuations of the output can be significantly reduced. This is obvious in figure 7 where the measurements are plotted as the ratio of the intensities vs. the distance of the light source to end-point-1. The choices of the order of the ratio and the parameter on the abscissa are arbitrary. The fit of the data to three parameters gave for the coefficients $\lambda_{short} = 0.88\text{m}$ and $\lambda_{long} = 5.83\text{m}$ and $cc = 1.058$. The intensity loss can be expressed as 1dB/m or a 50% loss after 6 m.

8. Discussion

Here we point out that the method of grouping the fibers and preparing them for optical contact with the PMTs is an integral part of the light output level. During the optical finishing procedures of the fiber-ends, it is important to handle with care in order to avoid scratches at any place along the fibers, even though they are double-clad. The expensive method of "diamond cut", used in the fiber optic industry, is not necessary here. A simple snipping of the end will suffice. The polishing of the ends was critical though. Placed in the finishing set up in small bunches (20 fibers at a time) with strain-relief mechanisms and a mechanical sanding apparatus composed of a slow rotating drum with high grade-number sandpaper minimized fluctuation in the resurfacing process. A monitoring and cooling system of the surfaces proved paramount during polishing. Finally the "mirror" finish of the fiber ends was achieved with micron-grade radial bristle discs (from the 3M company) commonly used in jewelry industry. Throughout our experience with the fiber bunching and finishing we found fluctuations in the light yield of about 30%.

The long component of the attenuation length measured here is very close to the extents of the magnetic field around the beam direction. The light output of the 20-layer full-size detector-module would be a factor of two more as compared to the half-size prototype. Including the attenuation of the intensity, that output is an average of 10 pe/MeV of light from each read-out channel after it is transported beyond the magnetic field. Outside that field and the vacuum region, commercial high-gain PMTs (e.g. the Burle tubes tested here) can be used. That method eliminates the need for complicated light-guide configurations or readouts close to the detectors. For example, magnetically shielded PMTs are very expensive for high volume projects. On the other hand, avalanche photodiodes (APD) are magnetically unaffected but require cooling and maintenance systems critical to their gain stability, which is not trivial if they are placed in rough vacuum.

9. Summary

A single-tile and one 10-layer prototype of the sweeping magnet γ-veto detectors of the KOPIO experiment were studied with cosmic rays. They performed within experimental specifications in light yield and time resolution. The light attenuation of the already embedded KMC-WLS fibers was measured as comparable to the size of the magnetic field in which the modules were intended to operate. That permits the assertion that these fibers are good enough for light transport out of the field and the rough vacuum regions especially if they are coupled to high-gain PMTs like the Burle 83112-511 that was also evaluated in this study.

Acknowledgements

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